TRANSPORT OF ROAD DERIVED SEDIMENT AS A FUNCTION OF SLOPE CHARACTERISTICS AND TIME

Acceptable Final Report
CHTroendle

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Submitted to: USDA Forest Service
Rocky Mountain Forest and Range
Experiment Station
240 West Prospect
Ft. Collins, CO 80521
Contract 28-C2-214

Submitted by: D. H. Campbell
J. D. Stednick
Water Quality Laboratory
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ABSTRACT

Distance of sediment movement downslope from water diversions on logging roads was investigated during the spring-summer (runoff season) of 1982 in a Colorado spruce-fir forest. Storm runoff was simulated by applying sediment-laden water at points of diversion from the road surface. Sediment flows were observed following twelve simulated and two natural storms at nine sites. Sediment movement was observed to decrease significantly after a few intense runoff events. Microtopography of the road surface rendered outsloping ineffective in preventing concentrated flow from being diverted at dips in the road. The primary source of sediment and controlling factor in downslope movement was rill erosion on the fillslope below these diversions, where transport capacity increased due to the steeper gradient and the uncompacted sidecast was easily detached.

Total sediment advance averaged 16.3 meters per site, the farthest measuring 37.5 meters. An equation to predict maximum downslope sediment movement given length and slope of the road segment and cover and slope of the hillside was developed based on modified factors from the Universal Soil Loss Equation. This regression had an R^2 of 0.77, and a standard error of 4.93 meters. If a safety factor of 2 standard errors, i.e., approximately 10 meters, is added to the predicted sediment advance, application of the equation in the location and design of roads should prevent sediment from reaching

stream courses 97.5% of the time for mean values of the predictor variables. The relationship is presented as a series of nomographs to be used by land managers in planning roads for timber harvest. Utilization of these guidelines should protect water resources while minimizing restrictions on road construction.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Accelerated sedimentation has been identified as the primary water quality problem related to forest management in the western United States. Activities associated with timber harvest, yarding and roads, result in disturbance of soils and vegetation, increasing susceptibility to erosion. This disturbance also alters the hydrologic cycle, generating more overland flow for detachment and transport of sediment. It is estimated that 90% of the sediment production from timber harvest can be attributed to roads (Megahan, 1972). Sediment yield increases of two to three orders of magnitude over undisturbed sites have been observed (Megahan and Kidd, 1971). Forest harvesting has been moving towards progressively steeper-sloped lands in recent years, intensifying the problem (King and Gonsior, 1980).

The greatest source of sediment is soil erosion caused when energy of raindrops or overland flow is sufficient to detach soil particles or aggregates. Transport continues until energy is no longer adequate to move the sediment, at which time deposition occurs. Large quantities of sediment may be trapped downslope from roadbed water diversions and in emphemeral runoff channels. A delivery index is used to quantify the portion of eroded sediment which reaches a given point downstream. This sediment will not affect downstream

quality unless remobilized by subsequent higher energy flow conditions. The goal of proper road design is to prevent sediment-laden flows from reaching stream courses, i.e., keeping the sediment delivery index for road derived sediment low.

Sediment in surface waters creates both economic and environmental problems. Turbidity may reduce light penetration, which may inhibit primary production. Fish and stream invertebrates may suffer from habitat damage as coarse bed material is covered with finer sediment. Aesthetics are compromised as clear streams are muddied. In addition, many streams serve as municipal water supplies, and increased turbidity may necessitate additional treatment. Sedimentation also causes changes in stream hydraulics which can do costly damage to roads and other structures.

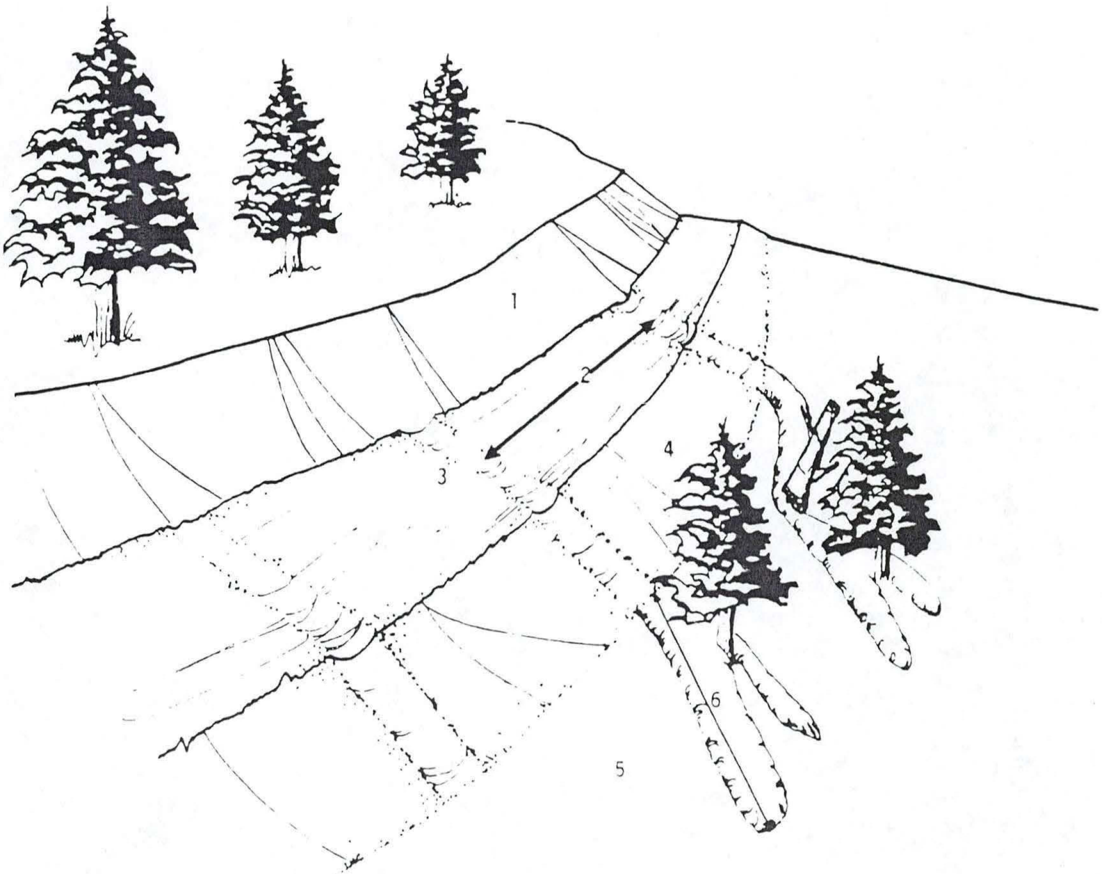
Climate, vegetative cover, slope, and soil characteristics are important in determining sediment yields from undisturbed sites. Road construction alters the latter three and generally increases erosion and transport of sediment for some time (Megahan, 1975). Removal of vegetation and the litter layer from soil surfaces exposes soil particles to the energy of raindrop impact, the primary agent of interrill erosion (Meyer et. al., 1975). The reduction in infiltration necessary for stability increases road surface runoff, which may be augmented by overland and subsurface flow from the cutslope and drainage area above it. As flow and the energy associated with it accumulate and become concentrated in channels, rill and gully erosion cause much larger volumes of sediment to be

detached and transported. Roads are designed to minimize concentration of flow through outsloping and frequent water diversions.

As sediment-laden runoff reaches the edge of the roadfill, it is dammed by debris and energy is dissipated by litter and vegetative cover. This reduces the energy available for transport, causing deposition which decreases the distance sediment will be moved. However, the actual processes which describe and the parameters that control the delivery of eroded material downslope are less well understood than those for erosion, and data for sediment delivery are scarce (USDA-Forest Service, 1980). In the discussion of sediment delivery in Water Resources Evaluation of Non-point Silvicultural Sources (WRENS), a sediment delivery index is presented with the acknowledgement that data to support the index does not exist, and more research is necessary to establish reliable estimates of sediment delivery.

Sedimentation processes occur on all of the features of a typical road segment (Figure 1). The cutslope is a steep bank on the uphill side of the road which consists of relatively stable material which was in place before the site was disturbed. Erosion may occur here if overland flow spills down the cutslope or if subsurface flow emerges on the bank.

The road surface is a bench of highly compacted material where most of the overland flow is generated. This surface is slightly outsloped in order to direct sheet flow to the outer edge of the road, where it can be diverted before concentration of flow occurs. At intervals, dips in the road are placed in order to divert any runoff



1. Cutslope.
2. Road surface, showing measurement of segment length between dips.
3. Dip (water diversion).
4. Fillslope.
5. Undisturbed forest floor.
6. Sediment flow, showing measurement of advance.

Figure 1. Characteristics of a typical forest road (after Haupt, 1959).

which may be flowing along the axis of the road. The distance between these dips, or road segment length, determines the total area which may contribute runoff to one of these water diversions.

As flow is diverted, either at a dip or anywhere along the outsloped road, it passes over the fillslope. This is a bank of uncompacted sidecast material with potential for erosion, especially below dips where water discharge may be high during intense storm events.

Once the sediment-laden flows reach the undisturbed forest floor at the toe of the fillslope, energy is dissipated by litter, debris, and vegetation, causing deposition of sediment. The infiltration rate is high, decreasing the water available for sediment transport and thus depositing sediment on the surface.

Two other features of road construction are not found on every segment but may be important in determining the distance of sediment movement. When the road is pioneered, cut timber is temporarily stored adjacent to the road, usually on the downhill (fillslope) side, and occasionally a dip may coincide with one of these log decks, diverting sediment-laden water between the logs. The log decks may then act as baffles to reduce flow energy and increase deposition during the period immediately after road construction when sediment movement is greatest.

The stumps from these right-of-way trees may be disposed of either by burning or by burial. Generally burial is used because it is quicker and easier, occasionally leaving a large area of bare disturbed soil immediately downslope from the road. If high energy

runoff is diverted over these burial pits, rill and gully erosion may result. Good management requires burial pits to be discrete relative to the road. Both log decks and burial pits occur infrequently relative to the number of water diversions along the road (at about a 1 to 5 ratio).

Road-derived sediment reaching the stream course has been shown to decrease exponentially with time since road construction (Megahan and Kidd, 1972; King, 1979; King and Gonsior, 1980). Significantly accelerated surface erosion was observed only during a few thunderstorms immediately following road construction. Re-establishment of vegetation is an obvious factor influencing stabilization but physical processes such as development of pavement and armouring may be involved as well. More easily eroded fine particles are readily transported, and surface erosion decreases as their availability is diminished.

Studies in Idaho indicated that on well-designed roads most sediment flows travel less than ten meters from the toe of the fillslope and occur soon after construction (Haupt and Kidd, 1965). Buffer strips of this width were recommended to capture all of the sediment being transported from the road disturbances. However, sediment movements of more than twenty meters were observed on the Fool Creek drainage of the Fraser Experimental Forest (Troendle, 1981).

Earlier studies of sediment transport along Fool Creek (Leaf, 1974) indicated little or no water quality degradation is to be expected from road construction with proper planning, construction,

and maintenance. A model was fitted to the Fool Creek Watershed based on sediment yield data collected by an in-stream sediment trap. This model predicted decreased sediment yield with time, as a function of topographic and road engineering characteristics (Leaf, 1974). It did not address the hillslope processes which are involved in determining sediment delivery to the stream.

A set of guidelines for road sediment control were developed for the Northern Rocky Mountain region (Packer and Christiansen, 1964). Factors affecting the distance sediment moves downslope were identified as cross-drain spacing (road segment length), kinds and spacing of obstructions, cover density, soil particle size distribution, and road age.

More recent work in the Idaho batholith (King, 1979) led to the conclusion that road design parameters may be important in predicting erosion, but downslope transport of the material was primarily controlled by slope steepness and the type and amount of cover. A significant decrease in sediment transport was observed during one year of study.

Other investigators (Haupt and Kidd, 1965) have reported similar trends after measuring sediment movement downslope from cross-ditches and in ephemeral channels. While there was much variability between sites, movement downslope had effectively ceased three years after roads had been put to bed; i.e., closed to traffic, water barred, culverts and bridges removed, and allowed to revegetate. The element of chance associated with relying upon natural weather systems to generate data was identified as a possible bias in this type of study.

There is a need for more data to establish the relationship between transport distance and slope characteristics, and determine the processes which cause sediment movement to diminish with time.

Much of the data describing the decrease in sediment yield with time has been collected on roads that were put to bed. In these cases, a dynamic equilibrium evolves from channel stabilization and erosion pavement development. However, roads receiving continuous use may not recover, or response may be much slower, as a result of continued disturbance. This effect has been demonstrated simply by limiting vehicle traffic in areas of the Deadhorse and Fool Creek watersheds in the Fraser Experimental Forest (Troendle, 1982).

Migration of sediment flows may be primarily a function of the source of newly eroded sediment, i.e., the volume of sediment being discharged at the edge of the road disturbance. This would imply that sediments previously deposited on the forest floor have been stabilized. Conversely, flow energy during successive storms may be sufficient to remobilize these sediment flows and they may extend farther downslope even in the absence of newly introduced material.

STUDY OBJECTIVES

The goal of this research was to provide engineers and land managers with a set of guidelines to minimize stream sedimentation from construction of forest access roads. A relationship was needed to predict sediment delivery downslope from the roads using maximum distance of sediment movement as the dependent variable and road design and hillside characteristics as predictor variables. Simulation of storm event runoff was used to ascertain that maximum movement was attained at various storm intensities. The model developed can be applied in the location and design of roads to minimize sediment reaching stream courses.

SITE DESCRIPTION

The study was conducted in the Fraser Experimental Forest, established in 1937 as a research area for the Central Rocky Mountain region of the National Forest system. It is located approximately 80 kilometers west of Denver, Colorado (Figure 2).

The climate is typical of the province, records from headquarters (elevation, 2743 m) indicate an average annual temperature of 0.6°C, with a mean of -10°C in January and 12.8°C in July (Alexander and Watkins, 1977).

Average annual precipitation for the entire forest is 74 cm, two-thirds of which falls as snow from October through May. About half of the annual precipitation becomes streamflow, which increases from a minimum in April to a peak in June (Alexander and Watkins, 1977).

The roads studied are located in the Deadhorse watershed, a tributary of St. Louis Creek which flows eastward from its headwaters on 3520 m Bottle Peak. These waters are tributary to the Colorado via the Fraser River.

The Deadhorse Valley is narrow and steep, consisting of gneiss and schist which have been subjected to a series of glaciations depositing alluvium and outwash on the valley floor (Retzer, 1962). The study area is at 3200 m elevation, with vegetation of

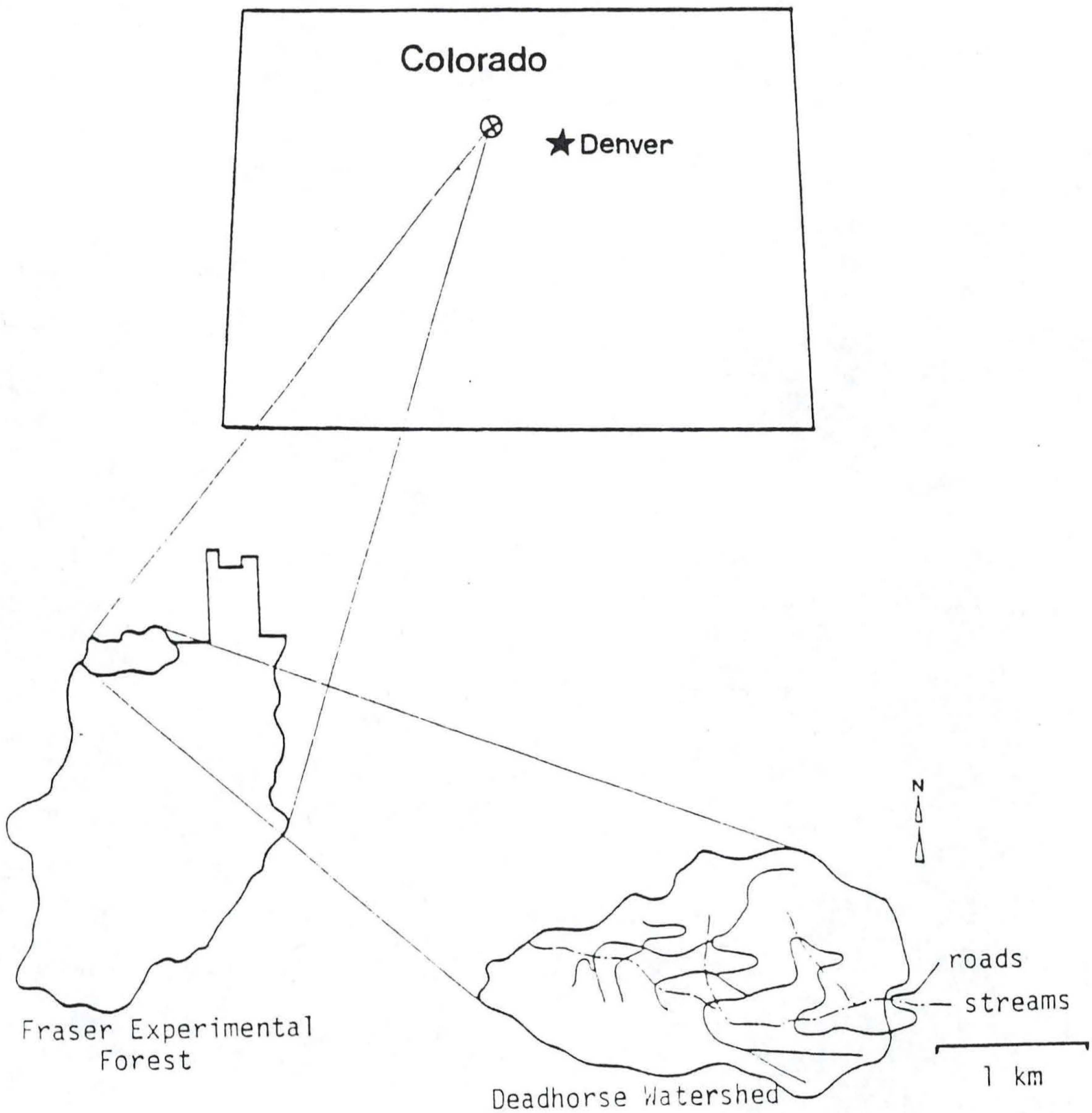


Figure 2. The study area.

predominantly Engelmann Spruce (<u>Picea engelmanni</u> (Perry) (Engelm.) and subalpine fir (<u>Abies lasiocarpa</u> (Dougl.) (Forbes). Ground cover is almost exclusively <u>Vaccinium spp.</u> of 5-10 cm height. The litter layer consists of a dense mat of needles 2-10 cm deep. A shallow mantle of stony sandy soils of the Bobtail and Darling series is developed from the metamorphic parent material. These soils have very high infiltration capacities so that overland flow on the undisturbed forest floor occurs only occasionally during peak snowmelt (Retzer, 1962).

The roads in the study area were pioneered in fall of 1981, and finished shortly after snowmelt in July of 1982. They are standard management roads, slightly outsloped, with dips at intervals to divert runoff from the road surface over the fillslope and onto the undisturbed forest floor. There was no logging and little vehicle traffic during the study period. Clearcutting in patches began some months later in fall of 1982. In addition to these primary study sites, a number of road segments similar in design but constructed some time earlier were observed after natural storms. The response of the older road segments is compared to that of the newer road segments in order to describe the effect of road maturation on sediment movement.

METHODOLOGY

In order to define the maximum distance of sediment movement, it was first necessary to describe the processes controlling transport and their changes through time. In particular it was necessary to determine if sediment flows are stable (i.e., no further advance would be expected) at some time after road construction.

Storm simulation was used to reduce the length of time necessary for downslope advance of sediment to cease or level off after the initial pulse anticipated following road construction. Changes through the sequence of events on the new roads was compared to observations of older, presumably stable roads where sediment movement was not evident. It was hypothesized that for a given storm magnitude, a stable condition develops after one or a few events, after which downslope advance of sediment would be small. Alternatively, movement might show little attenuation through the sequence of events, leaving maximum distance of transport undefined.

Water was discharged from a 4000 liter tank using irrigation pipe to transfer the water to the edge of the road at dips which function as water diversions. Burlap was used to dissipate energy and prevent erosion at the point of pipe discharge.

Intensity of simulated storm runoff (measured in cm/hr) was regulated by an adjustable valve on the water tank, calibrated and

checked periodically by 1) measuring the amount of time necessary to fill a vessel of known volume at the point of discharge; and, 2) measuring the time necessary to empty the entire tank. Natural and simulated storms greatly exceeded the low infiltration capacity on the compacted road surface, so a runoff coefficient of 1 was assumed. Runoff (in cm) from the road surface due to natural events is thus equivalent to rainfall measured at a precipitation gauge located just below the study area.

Most sediment movement from forest roads in this region occurs during intense thundershowers of short duration (Troendle, 1982). Duration of artificial storms was held constant at 30 minutes; volume of water discharged was varied by increasing the flow rate (runoff intensity). At highest intensities, duration was limited by the capacity of the tank and was less than 30 minutes. A gradual progression from light to heavy storms was chosen, with 2-3 storms being applied at each level of intensity. This sequence tested the hypothesized response of sediment advance decreasing over time, as long as storm intensity did not increase.

In order to maintain similar antecedent moisture conditions between stations, storms of a given intensity were applied at all sites before stepping up to a higher intensity, which provided at least a two-day interval between storms on individual sites. An exception was the last two storms, which were done approximately one hour apart at each station to approximate a storm of that intensity with longer duration (and greater volume of discharge) than was possible with one tank.

For each artificial storm, flow rate at the diversion (in liters/minute) was equal at all stations, while equivalent runoff intensity for each road segment (in cm/hour) varied according to segment length. Runoff intensity (R.I.) for artificial storms was calculated as:

$$\text{R.I.}\,(\text{cm/hr}) = \frac{(\text{volume discharged, liters})(1000\text{cm}^3/\text{liter})(10^{-4}\text{m}^2/\text{cm}^2)}{(\text{road seg. length, m})(\text{road width, 3.1m})(\text{duration, hours})}$$

Flow rate and runoff intensity estimates were approximations for natural storms. Flow rates varied with area of road surface contributing overland flow. Road width is relatively constant, therefore flow rates were determined by road segment length. Runoff intensity in cm/hr was equal at all stations during natural events (Table 1).

Sediment was added at a concentration of approximately 1000 mg/l to represent sediment in runoff waters on road surfaces during precipitation events. Concentrations were calculated from measurements of suspended solids taken at the edge of the road during natural storm events. This experimental design allowed natural erosion processes to occur during storm simulations on the fillslope, which is the largest source of sediment (Megahan, 1972). Particle size fractionation was analyzed on samples of sediment transported from the road and deposited on the forest floor by earlier storms, and sediment added at the edge of the road had approximately this particle size distribution.

Table 1. Runoff intensities for different storm events and segment lengths. Runoff intensity was increased through the sequence of artificial storm events and varied among the stations according to road segment length.

	Runoff intensities in cm/hr.				
Artificial Storm No.	1,2,3	4,5	6,7	8	9,10,11,12
Segment length (m) 30	1.9	3.8	7.7	15.4	20.5
60	1.0	1.9	3.9	7.7	10.2
90	0.6	1.3	2.6	5.1	6.8
120	0.5	0.9	1.9	3.8	5.1

Road and slope variables were measured as follows:

Segment length (SEGL, m) was the distance measured from the water diversion upslope along the road axis to the drainage boundary (usually defined by another diversion). It was the sum of two distances where a single diversion lay in a low spot, draining a segment extending in both directions along the road. The segment length parameter was a measure of the drainage area contributing surface runoff at each station.

Segment slope (SEGS, %) was the percent slope of the road surface measured along the axis of the road.

Hillslope (HILS, %) was the percent slope of the hillside measured below the water diversion.

Configuration (CONF) was the shape of the slope below the water diversion. Concave shape was designated by a "0", flat shape by a "1", and a convex shape by a "2".

Cover was measured on a 1 meter square placed on the slope where water is diverted. This grid has twenty evenly spaced points which are then surveyed to find the percent cover of vegetation, debris, litter, mineral soil, and rock. Vegetation (VEG, %) and debris (DEB, %) were later added together to form a single parameter, cover (COV, %), which reflected both the resistance to erosion and the dissipation of energy that these cover types afforded compared to bare soil or litter.

Depth to mineral soil (DMS, cm) was measured on the same grid and the arithmetic mean was recorded for each site. Included in the depth was debris in contact with the soil. Not included was debris or

vegetation which was not touching the ground at the point being surveyed.

Fillslope length (FILL, m) was measured as the distance from the edge of the road surface to the toe of the fillslope. Road runoff was diverted over this steep reach of bare soil with potential for rill and gully erosion. Fillslope steepness (FILS, %) was measured along these same transects.

The dependent variable, sediment advance (ADV, m) was the distance from the toe of the fillslope to the farthest point downslope where deposition from runoff was observed. This sediment, generally being of much lighter color and resting on top of an 0 or A soil horizon containing some degree of organic matter, was easily identified. In rare cases where the origin of the material was questionable or quantities were miniscule, a note was made but no advance was recorded.

Model development was conducted on the Colorado State University Cyber 170 computer system, using the BMDP statistical package (U.C.L.A. Department of Biomathematics, 1981) to run multiple regressions using various combinations of the independent variables. The best equations were then examined in greater detail.

RESULTS

Road segment and slope variables were recorded (Table 2). Total sediment advance at each station by storm event was tabulated (Table 3). The cumulative advance of sediment at all stations was plotted against cumulative runoff depth (Figure 3). The greater the slope of the line on this graph, the farther sediment moved per centimeter of runoff. A large percentage of the total movement occurred during just a few storms, and these storms contributed a disproportionate share of the advance given the size of the event.

Minor sediment migration had occurred before the study began as a result of small events in Fall, 1981 and snowmelt prior to final grading of the roads in July, 1982. During the study period, twelve simulated storms and two natural storms occurred.

A thunderstorm on the afternoon of July 26, 1982, just a few hours after final inspection of the new roads was completed, caused advance of sediment downslope greater than all previous storms and snowmelt combined. There was no significant sediment advance measured on old road sites. Approximately 2.2 cm of rain fell in a period of 30 minutes. A return interval of 10 years is indicated by U.S. Weather Bureau Technical Paper 40 and the NOAA Weather Atlas. Sediment advance was great during this event, and deeply cut

Table 2. Characteristics and total sediment advance for each station.

STA #	SEGL m	SEGS %	HILS %	CONF -	VEG %	DEB %	DMS cm	FILL m	FILS %	ADV m
1	99	9	37	1	70	0	2.8	3.2	70	18.7
6	114	16	40	0	0	0	35.0	7.3	70	37.5
11	43	8	23	1	35	20	3.4	2.7	50	21.9
15	88	12	31	1	5	20	1.9	16.1	70	19.5
17	66	16	15	1	40	45	6.3	2.6	15	10.9
18	111	10	23	1	45	15	2.5	3.1	70	15.1
21	83	10	21	1	25	70	24.5	10.1	50	8.2
30	72	10	26	0	0	60	5.8	2.3	72	3.3
23	106	11	46	2	80	10	9.3	2.9	62	11.7

SEGL - road segment length
SEGS - road segment slope (grade)
HILS - slope of hillside on which road is located
CONF - configuration of hillside: 0 - concave; 1 - flat; 2 - convex
VEG - vegetative cover
DEB - debris cover
DMS - depth to mineral soil
FILL - fillslope length
FILS - fillslope steepness
ADV - total sediment advance

Table 3. Cumulative sediment advance for individual stations by storm event.

STA #	THRU 7-26	NS 7-26	AS1	AS2	AS3	AS4	AS5	AS6	NS 8-13	AS7	AS8	AS9	AS10	AS11	AS12
01	1.4	1.8	2.9	3.0	3.0	3.0	3.0	3.0	16.1	16.1	16.5	16.5	18.2	18.2	18.7
06	4.3	23.3	23.3	23.3	23.3	23.3	23.3	25.8	31.0	31.0	33.2	33.2	33.2	37.5	37.5
11	0	4.8	4.9	5.5	6.5	6.5	6.5	6.5	21.4	21.4	21.4	21.9	21.9	21.9	21.9
15	0	3.2	3.8	3.8	3.9	4.4	5.1	6.3	14.9	15.7	15.7	16.4	17.4	18.5	19.5
17	0	4.5	4.5	4.5	4.5	4.5	4.5	9.8	10.9	10.9	10.9	10.9	10.9	10.9	10.9
18	0	2.8	2.8	4.6	4.6	4.6	4.6	4.6	12.1	12.6	13.4	15.1	15.1	15.1	15.1
21	0	0	0	0	0.6	1.2	1.2	2.3	6.0	6.0	7.1	7.1	8.2	8.2	8.2
30	0	0.7	0.9	0.9	0.9	0.9	0.9	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
23	0	2.0	2.2	2.2	2.2	2.2	2.4	2.8	10.7	10.7	10.7	10.7	11.7	11.7	11.7
Tot	5.7	43.1	45.3	47.8	49.5	50.6	51.5	64.4	126.4	127.7	132.2	135.1	139.9	145.8	146.8
51	10.3	10.3							10.8						
52	42.2	42.2							70.4						
53	0	0							0						
55	23.7	23.7							23.7						
56	8.0	8.0							11.1						

Stations #01 - 23: new road segments

Stations #51 - 56: old road segments

NS - Natural Storms
AS - Artificial Storms

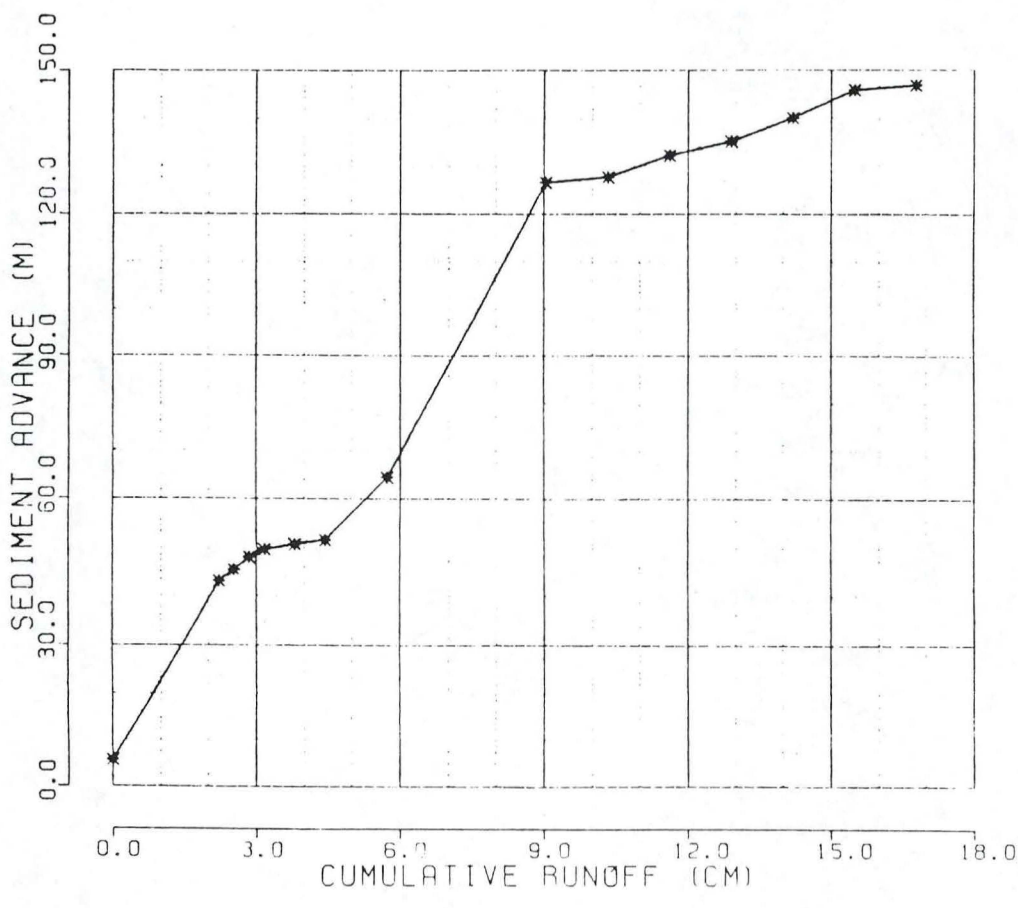


Figure 3. Cumulative sediment advance for all stations versus cumulative runoff. Slope of the graph indicates sediment movement per centimeter of runoff for each storm event.

well-armoured channels were formed in the sidecast material of the fillslope.

The first five artificial storms (AS-1 through AS-5) were of relatively low energy, sufficient neither to remobilize sediment deposited earlier nor detach and transport new sediment farther than previous flows. AS-6 did cause much sediment movement, primarily at two stations whose short segment lengths had contributed less runoff during the natural storm. The higher discharge generated rill erosion on the fillslope, introducing a new supply of sediment which was transported beyond previous sediment flows.

A thunderstorm on August 13, 1982, caused approximately 3.3 cm of precipitation in less than 30 minutes. A return interval of 100 years is indicated by TP-40 and the NOAA Atlas, however, actual return intervals for such high mountain areas influenced by orographic effects are probably shorter. Advance of sediment for the August 13 storm was even greater than that on July 26. Observations of sediment flows on the old roads indicated that this was an unusually high magnitude event, not recently if ever having occurred since the old roads were constructed. Sediment advanced on these old road sites where no movement had occurred during previous natural or artificial storms (Table 3).

There was little sediment advance caused by application of AS-7, contrasting movement during AS-6 which was of the same intensity. The thunderstorm which occurred after AS-6 had flushed the system of sediment which could be transported by flows of that energy. The next four artificial storms, while of approximately the same intensity as

the natural storm of July 26, caused moderate transport at a few stations. Movement per cm of runoff was far less than for the first natural storm as illustrated by the flatter slope of the curve on the storm events graph (Figure 3).

Outsloping of roads minimizes flow energy available for sediment transport by diverting runoff onto the fillslope before it can concentrate on the road surface. However, microtopographic features may interrupt this drainage, concentrating water and sediment at dips instead of allowing diffuse flow over the fillslope. Such interruption occurred on all of the sites studied, causing little if any of the runoff to be diverted from the road before reaching the dip. Two prevalent causes were berms resulting from final grading of the roads and wheel ruts from vehicle traffic, especially when the roadbed was wet. Other investigators (Haupt and King, 1965) have suggested that outsloping not be used in construction of forest roads.

While flows at the point of diversion are generally predictable from the road segment length (which determines area contributing overland flow), in some cases the roadcut may intercept subsurface flow which is difficult to quantify. This occurred on one of the segments studied (Station 11). During the most intense precipitation event soil piping caused rill erosion on the steep cutslopes and increased both water volume and energy of flows on and below the road. Deposition of this material occurred on the relatively flat road surfaces just below the rills. Farther downslope, road surface erosion from concentration of these high flows was evident. This site did not fit the predictive model that was developed, which relies only

on segment length and slope to index the quantity and energy of the flow available for sediment transport.

Two study sites (Stations 15 and 21) consisted of segments where dips diverted runoff onto stump burial pits. There is high potential for sediment movement from these areas, especially where energy is high and channels become established on the long barren slope. At one site (Station 21) the sideslope was not steep, and little rilling of the bare soil occurred since sheet flow predominated.

Diversion over a burial pit of steeper slope (Station 15), however, caused sediment erosion and transport which, unlike the other stations, remained in progress through the final storm simulation. Deep channels near the edge of the road were fairly stable at the storm intensities applied but farther downslope in an anastomosing flow regime sediment remained in motion. It is possible that given a few more storms of similar magnitude, a stable condition may have been reached due to reduction in sediment supply from the established channels.

On the other hand, where a dip diverted flow into a log deck (Station 17), ponding occurred and flow became diffuse, depositing nearly all of the sediment in spaces between the logs. This appeared to be an effective, if accidental, management practice.

Different sediment transport processes occurred in three distinct areas - the road surface, the fillslope, and the undisturbed forest floor. The road surface and the fillslope were sediment source areas where erosion occured. The road surface was dominated by interrill erosion, for which raindrop splash is the most important mechanism of

particle detachment (Meyer, et. al., 1975). Comparison of suspended solids samples taken at the edge of the road surface with calculations of the volume of material eroded from rills on the fillslope indicated that the amount of sediment contributed by runoff passing over the sidecast was 2 - 10 times greater than that produced on the road surface. The steeper slope, concentrated flow, and less compacted soil on the fillslope caused rill formation in the sidecast at all of the sites. Sediment transport was limited by the capability of the flow to detach particles in this region. Initially this was controlled by the relationship between energy of the flow and its transport capacity, as the rills gradually reached an equilibrium geometry for a given magnitude of runoff. Subsequent storms of greater magnitude deepened and widened these channels, eroding more soil. These rills also developed a protective pavement, minimizing detachment of material during equal or lesser flows which followed. After a few intense storms, the channels were fairly stable and a decrease in sediment production was observed. This is similar to observations of gulley morphology and sediment yields in arid zones (Heede, 1975).

Once runoff passed onto the undisturbed forest floor, infiltration generally occurred within a short distance. Obstructions such as litter, debris, and vegetation reduced the energy available for sediment transport, and deposition occurred. As litter became covered by sediment and soil pores clogged, infiltration capacity and energy dissipation decreased causing more sediment-laden water to be transported farther downslope. These deltas or fingers of sediment

flow continued to grow as long as there was a supply of sediment. Erosion and deposition changed the control and pattern of water and sediment flows, sometimes creating a braided pattern if the slope was flat or convex rather than concave. Remobilization of sediment previously deposited occurred due to these shifts in the flow caused by newly deposited sediment upslope. Transport of both old and new sediment was, then, dependent on a source of freshly eroded material, which was rilling on the fillslope. The advance of sediment downslope was attenuated once these rills became stable.

It is reasonable to assume that the distance of sediment advance reached at the end of the study was the maximum which would be expected given the occurrence of two unusually intense natural thunderstorms during a period when the roads were most susceptible to sediment detachment and transport, i.e., just after disturbance. This is supported by results during the final artificial storm sequence, which showed little movement given the magnitude of the simulated runoff. Sediment advance during the final artificial storms is far less per cm of runoff than during the natural storm of July 26 (Figure 2), which had roughly the same intensity. It appeared that a condition had been reached in which little further advance would occur given the storm events experienced.

Table 4. Summary of data used in predictive model.

STA #	SLS	COV %	SF	ADV m
1	9.34	70	9.69	18.7
6	27.53	100	10.74	37.5
15	12.71	05	6.88	19.5
17	12.13	85	2.25	10.9
18	12.27	60	5.63	15.1
21	7.93	95	3.83	8.2
30	6.41	60	5.33	3.3
23	13.24	90	12.92	11.7

SLS - segment length-slope factor
COV - cover (vegetation + debris) on hillside
SF - slope factor of hillside
ADV - total sediment advance

DISCUSSION

Using the maximum distance downslope from the road where sediment was deposited after this stable condition had been reached, multivariable analysis was used to develop an equation to predict maximum sediment advance given characteristics of the road and hillslope. It was recognized that it would not be possible to use all of the independent variables measured, rather the best combination with fewest variables was sought.

The model developed is based on three independent components (Table 4): 1) a road segment length-slope factor (SLS), which is an index of the volume of water and sediment reaching the point of diversion for each road segment, 2) a hillside slope factor (SF) which expresses the energy of the flow as it passed over the undisturbed forest floor, and 3) percent cover (COV) which indexed the dissipation of energy that attenuated sediment flows.

The first component (SLS) was taken from the Universal Soil Loss Equation (USLE) (Wischmeier, 1978). The USLE predicted erosion rate per unit area and included a length-slope factor which may be divided into a length term and a slope term:

length factor	slope factor
$SLS = \dfrac{SEGL}{22.1}^{1.5}$	$65 \sin^2\theta + 4.64 \sin\theta + 0.065$

SLS: road segment length-slope factor

SEGL: road segment length in meters

Θ: road grade in degrees (from SEGS in %)

In applying the USLE to calculate erosion rate per unit area, the length term accounted for greater erosion where runoff accumulated on longer slopes. For example, all else being constant, more surface erosion was expected from an area with a lower drainage density than from an area similar in all respects but with more closely spaced channels. The latter case minimized accumulation of overland flow, the primary agent of rill erosion. An exponent of 0.5 applied to the length term best expressed this relationship (Wischmeier, 1978).

Conceptually, the model presented here uses the length-slope factor as an index of the volume of water and sediment being delivered at the point of discharge from each road segment. This volume was dependent on the contributing road surface area, and since the width of the roads was relatively constant, segment length determined the contributing area. In this application the standard USLE length-slope factor that accounted only for accumulation of runoff on longer slopes was multiplied by the length term to also account for the source area of road surface for each segment. This resulted in a total exponent of 1.5 for the length term. The coefficients were formulated to relate various conditions to a control site; while they were not important in this study, they are included to make the length-slope factor consistent with other applications. The factor gave a good estimate of the energy available in overland flow on the road surface,

both for erosion and transport of sediment. This in turn was an index of the sediment load and water discharge at the road edge. Values of the SLS for various segment lengths and slopes were presented in a nomograph (Figure 4).

The second term in the model was the steepness of the hillslope on which runoff was diverted, which again determined the energy available to transport sediment over the forest floor, as well as the distance water flowed before infiltration was complete. It was expressed as the slope factor (SF) defined in the USLE (Equation 2) where θ for this term was the hillslope (HILS) below the road in degrees.

The third term was a measure of the percentage of the forest floor which was not bare soil or litter. The two types of cover which appeared to attenuate sediment flows were vegetation (primarily vaccinium) and debris (anything larger than twig and needle sizes). These were inversely related, since the same plot cannot be covered both by 100% vegetation and 100% debris. They were thus summed in a term labeled "cover" (COV).

The equation developed from a least squares regression to predict sediment advance from the three independent variables was:

$$Y = -0.53 + 1.5(SLS) + 0.28(SF) - .063(COV)$$

Y = sediment advance in meters

SLS = segment length-slope factor, from modified USLE term

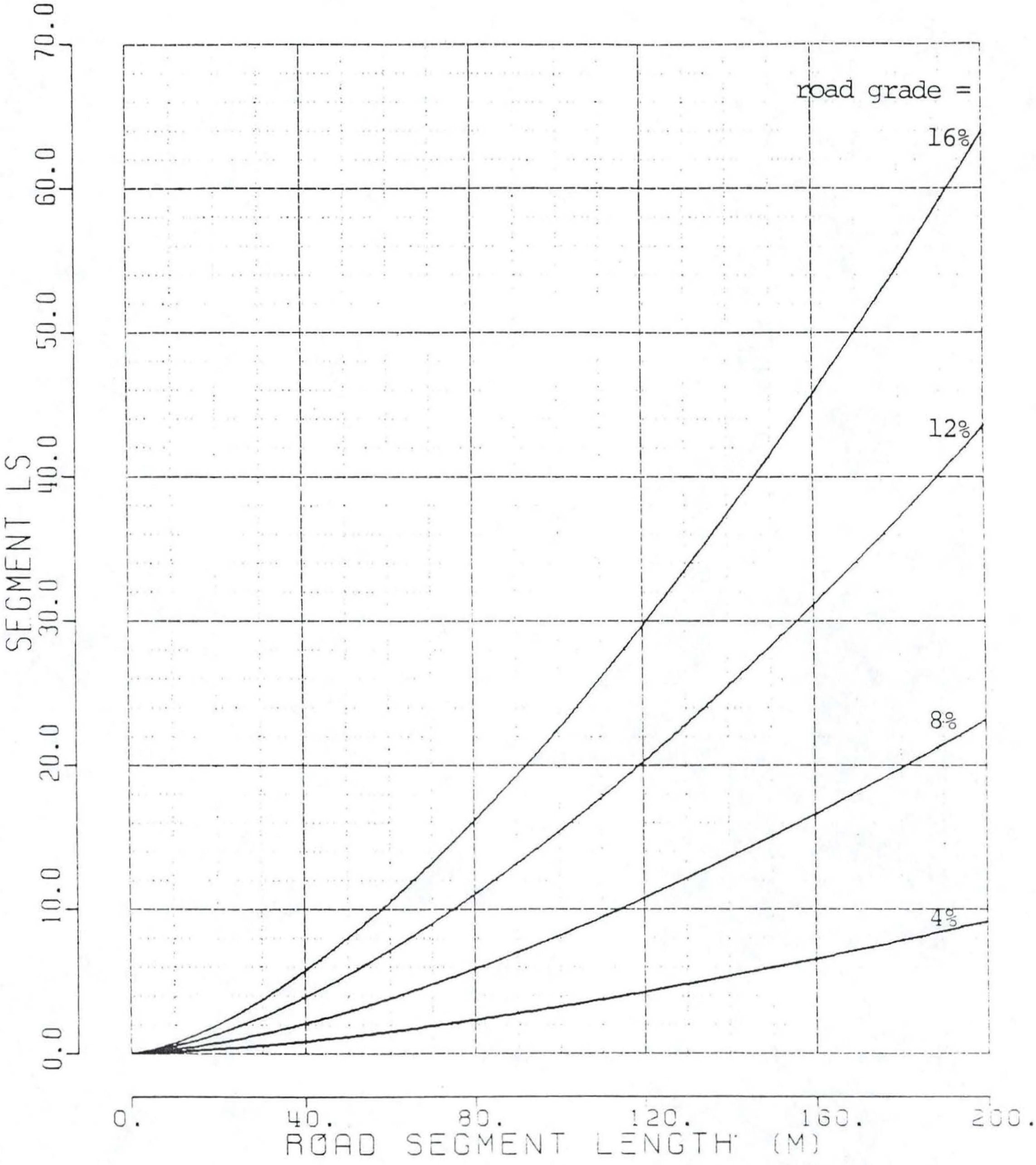


Figure 4. Road segment length-slope factor given road grade and segment length. Example: A 120 meter segment with a grade of 12% has a segment LS of 20.0.

SF = slope factor of hillside on which runoff is diverted, calculated from "HILS" in % using USLE relationship

COV = cover (vegetation + debris) in percent of hillside on which runoff is diverted.

The coefficient of determination (R^2) for this equation, adjusted for degrees of freedom, is 0.77, which means that 77% of the variability in total sediment advance among stations was explained by the three independent variables. This relationship is significant at $\alpha = 0.03$. The standard error was equal to 4.93 meters, which suggests that if a safety factor of 2 standard deviations, i.e., about 10 meters, were added to the sediment advance predicted, the distance calculated will be the maximum sediment advance 97.5% of the time for mean values of the predictor variables (SLS, SF, and COV).

Rearranging the equation, it can be applied to the design and location of a forest road for any particular site in order to minimize road sediment from entering stream courses. Generally the easiest and most reliable control measure will be spacing of water diversions on the road surface. Entering known values of cover and steepness of the sideslope, and using distance to the stream plus a safety factor for maximum sediment advance, the equation can be solved for the segment length slope factor. From this and knowing the grade of the road, a segment length can be calculated which will be equal to the spacing between water diversions on the road. These calculations are presented as nomographs (Figures 5-7).

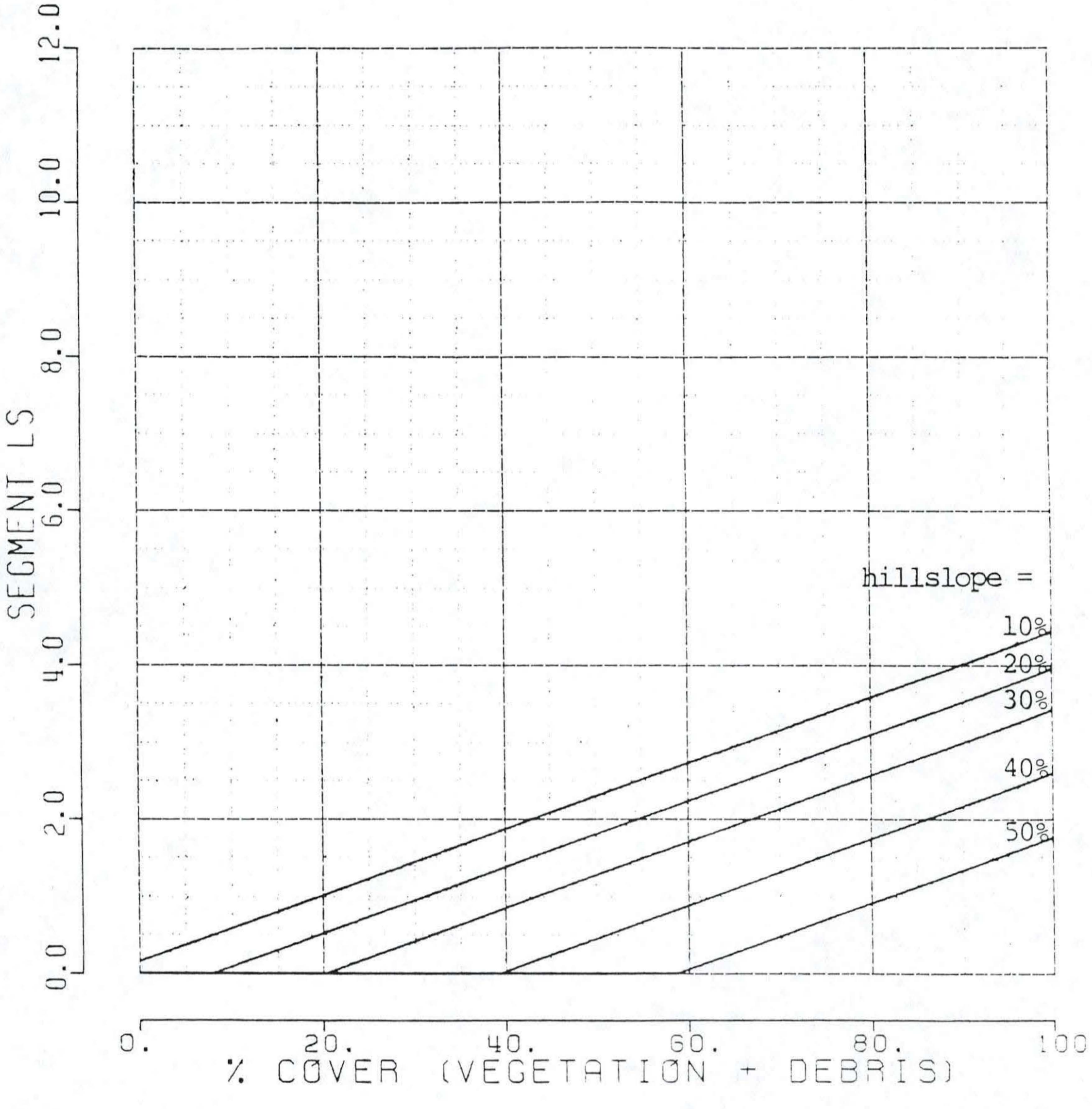


Figure 5. Relationship between segment length-slope factor, hillslope, and cover for zero sediment advance. Example: For a 10% slope with 20% cover, a maximum segment LS of 1.00 is recommended for zero sediment advance.

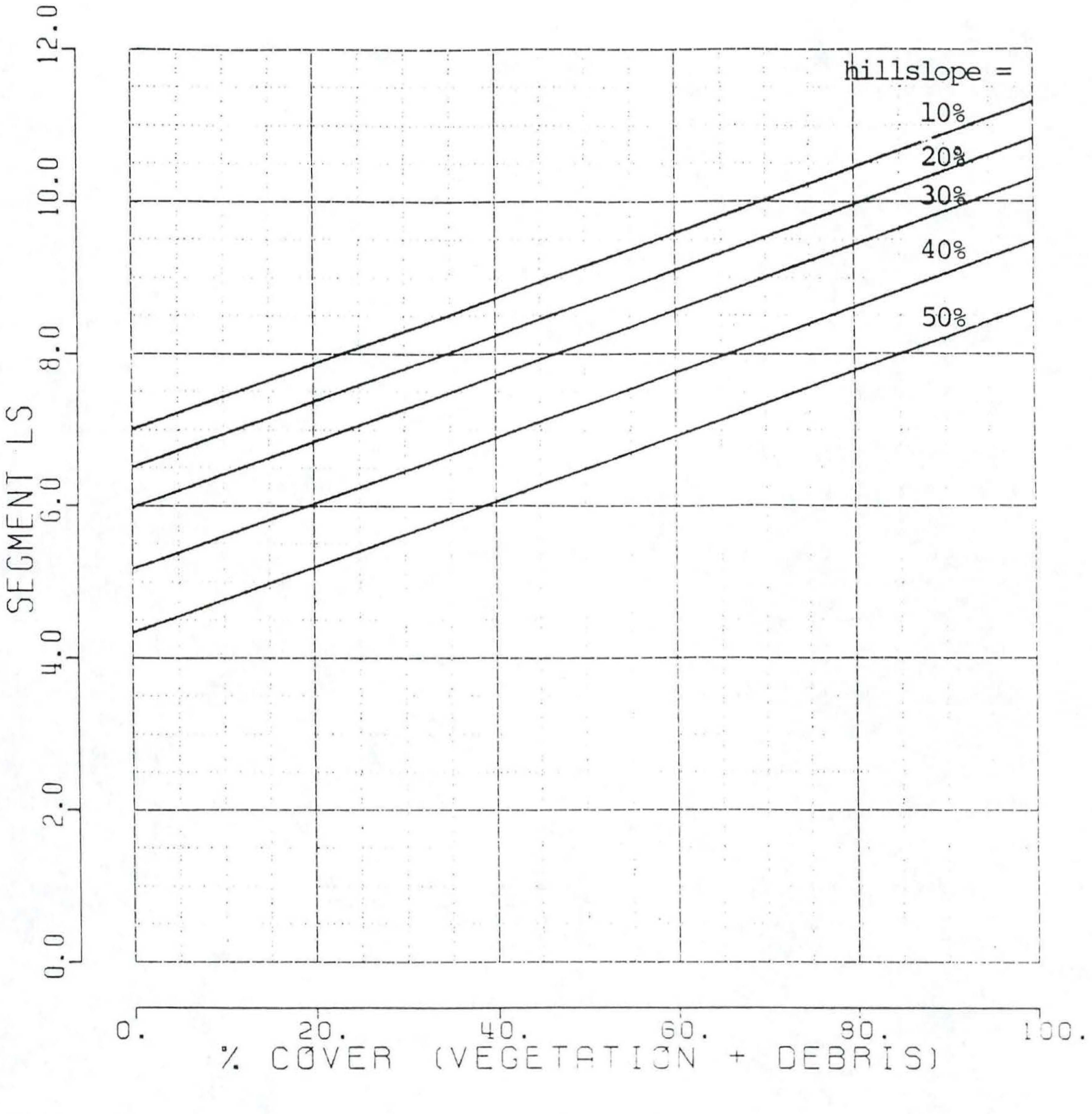


Figure 6. Relationship between segment length-slope factor, hillslope, and cover for sediment advance of 10 meters. Example: For a 30% slope with 40% cover, a maximum segment LS of 7.65 is recommended for a sediment advance of 10 meters.

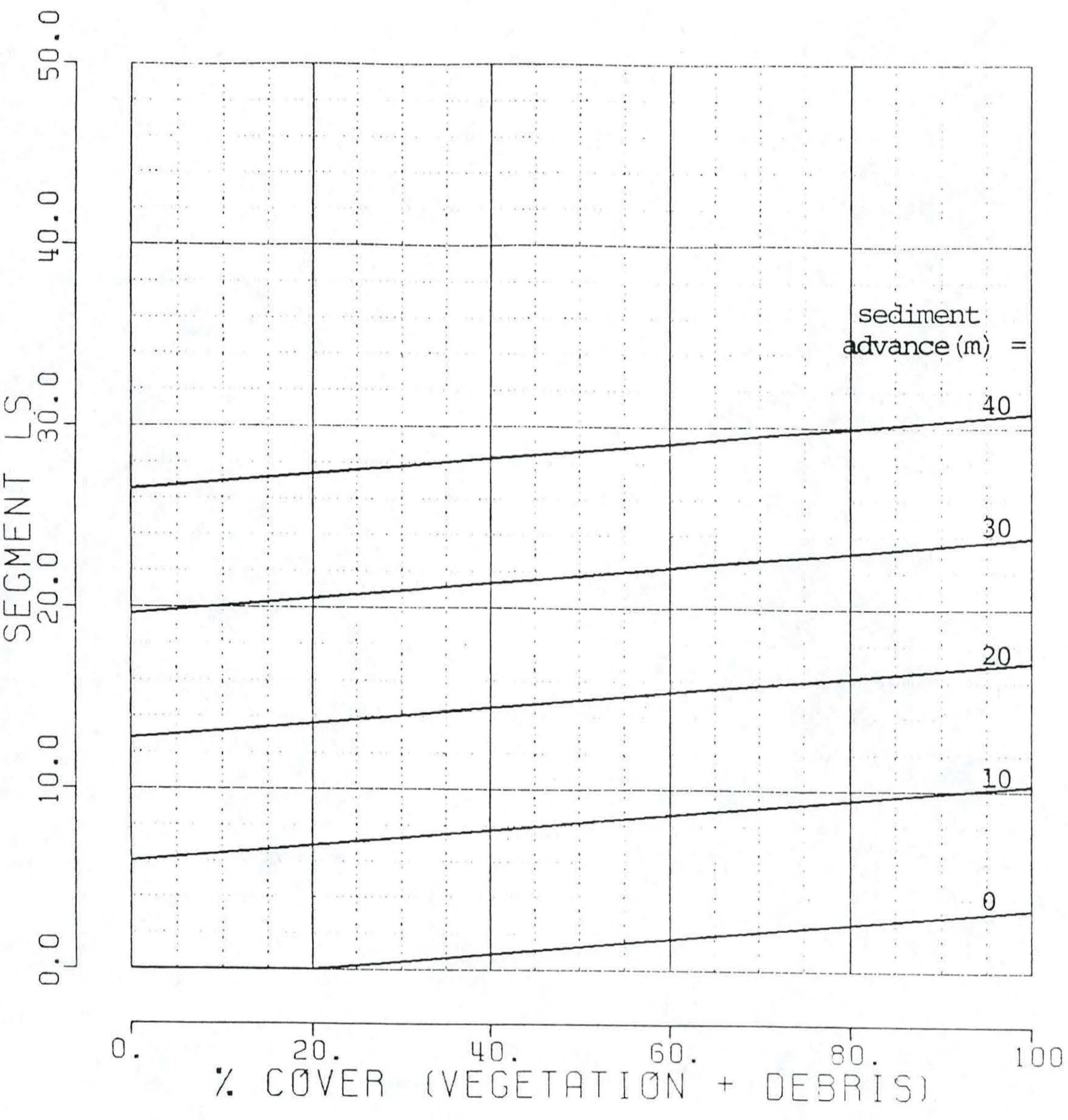


Figure 7. Road segment length-slope factor versus cover for predicting various distances of sediment advance on a 30% slope.

Application of the predictive relationship using the nomographs can be illustrated by starting with characteristics of a proposed road, calculating the sediment advance, accepting or rejecting the magnitude of advance and if rejected, suggesting alternatives which would meet the model criteria. Suppose a road segment of 12% grade and 80 m length is proposed on a 30% hillslope with 60% cover, located 20 meters from the stream.

A safety factor of 10 meters (2 standard deviations) is first subtracted from distance to the stream to get an acceptable predicted sediment advance of 10 meters. The nomograph for 10 meters sediment advance (Figure 6) must then be used to calculate an acceptable set of road and slope characteristics. Using the information given, 30% hillslope and 60% cover, the acceptable segment LS is about 8.6. However, the segment LS for the proposed road segment of 12% grade and 80 m length is 11.0 (Figure 4), therefore, an unacceptable advance of sediment is expected, possibly entering the stream.

Alternatives can then be examined. The first would be to locate the road farther from the stream, say 10 m farther than the previous case for a total buffer strip width of 30 m. Predicted sediment advance is now 20 m (retaining a safety factor of 10 m). Casual inspection of the nomograph (Figure 7) indicates that the criteria are easily met in this case.

In some instances it may not be possible or desirable to relocate the road segment, therefore, 10 meters predicted sediment advance must be used while altering other characteristics. Hillslope modification would be impractical, but cover could be improved by placing slash or

other material on the forest floor. If cover were improved to 100% and hillslope remained 30%, an acceptable segment LS of 10.5 is calculated (Figure 6), which is nearly that of the proposed segment.

Another alternative is to change characteristics of the road segment. Using the original calculation of acceptable segment LS of 8.6, segment length can be held constant at 80 m, limiting road grade to not greater than 10% (Figure 4).

The final possibility would be to hold road grade constant at 12% and reduce segment length to 65 m to attain the acceptable segment LS of 8.6. In practice, this is generally the most useful and cost-effective choice, since road grade and loation (distance to the stream) are often determined by necessity for timber access and improvement of cover has a small effect relative to decreasing segment length. Adding additional water diversions on the road decreases segment length without necessitating major redesign of the road network.

Most of the road system in the Deadhorse drainage is located sufficiently far from the stream that no sediment would be expected to reach the water course. In this case the primary concern is to prevent surface water and sediment flows from reaching downslope road segments, and augmenting impacts of water and sediment generated on the downslope segment. In addition to altering road design parameters to shorten the distance of sediment movement, there is the option of simply locating roads farther apart.

In summary, this model is applied by examining characteristics of a proposed road segment to see if sediment movement is expected to

reach downslope stream courses or roads. Where the predicted sediment advance is less than the distance to roads or streams, sedimentation problems are not anticipated. Where sediment advance is expected to be unacceptable, road design can be modified to meet the model criteria. Options available are changing the road location, improving cover on the hillside, changing the road grade, and shortening the segment length.

Where roads must cross streams, there is little or no undisturbed area below the toe of the fillslope to allow deposition. The one site in the Deadhorse watershed where significant amounts of sediment were reaching the stream was at such a location, where the stream passed under the road through a culvert and emerged at the toe of the long steep fillslope. Surface flow on the road was contributed from a long segment and diverted onto the sidecast, where deep rills were eroded. Deposition of this material in the stream was evident for a considerable distance. Most of this problem could be avoided simply by insloping the road at this point, allowing the runoff to enter the culvert rather than flow over the erodible fillslope.

Elsewhere that unacceptable sedimentation is anticipated based on the model presented, management practices could be implemented to mitigate downslope impacts. Slash may be placed in the path of flows on the fillslope to dissipate energy available for transport of sediment. While more costly, slope stabilization practices commonly utilized in suburban construction may be applied on particularly troublesome locations. In studies on granitic soils in Idaho, either

jute mesh or asphalt straw mulch, in combination with grass seeding, reduced fillslope erosion by about 97% (Ohlander, 1964).

Results of this study support and complement findings of previous investigations in other regions. Re-establishment of vegetation is more rapid in forests of the Appalachian Mountains and the Pacific Northwest due to the milder and wetter climates. When saturated, soils of the Northwest are susceptible to mass failure, a process of greater importance in that area than the surface erosion which predominates in the Rockies (Beschta, 1978). Research of road design effects on sedimentation has been conducted for many years in the Northern Rockies of central Idaho. The processes observed and the management practices recommended are very similar to those described in this work (Packer and Christiansen, 1964), except that watershed characteristics in that region demand that more conservative models be applied. Soils of the Deadhorse watershed are described as "unusually stable against erosion" (Retzer, 1962) while the granite derived soils of central Idaho are among the most easily eroded (Megahan, 1975). Additionally, sideslopes in the Deadhorse watershed average around 40%, while those studies in Idaho ranged from 65-75%. Mass failures observed in the Northern Rockies, even some years after road construction disturbance, are not anticipated in Colorado.

CONCLUSIONS

Sediment migration downslope from roads may be expected to diminish rapidly after a few intense thunderstorms have occurred. Most of the sediment is eroded from rills on the fillslope, which are rapidly cut to a depth and width to contain a given flow. Subsequent events of equal or less discharge cause little erosion of these well-paved channels.

Very little sediment actually reached the stream course of Deadhorse Creek following construction of the roads studied. In most cases, road segments are located sufficiently far from the stream to allow all sediment to be captured on the forest floor and road surface runoff to infiltrate. By following a simple set of guidelines such as those presented here, and exercising good judgement where special cases are involved, it is reasonable to expect no significant sedimentation problems in watersheds where roads are to be constructed.

Outsloping cannot be relied upon to prevent concentration of flow on the road surface and at water diversions. Observations here and elsewhere indicate that variations in the microtopography may interrupt the drainage pattern and make outsloping ineffective. When outsloping is used, water diversions should still be spaced assuming that all runoff will reach the diversions.

Stream crossings with culverts should be insloped in order to minimize rill erosion on the fillslope, since there is no undisturbed area below to mitigate sedimentation impacts on the stream. Diversion onto burial pits should be avoided.

Subsurface flow interception must be considered a special case - generally it is difficult to predict its occurrence until the road is actually constructed. When subsurface flow emerges on a cutbank, mitigative measures should be implemented such as diverting road surface flows immediately above and below the seep in order to minimize discharges at any given point.

The model:

$$Y = -0.53 + 1.5(SLS) + 0.28(SF) - .063(COV)$$

where SLS is the segment length-slope factor, SF is the hillside slope factor, and COV is percent cover, was developed under a set of soil and vegetation conditions which are specific but common in the Central Rockies. It should be useful given the construction of standard management roads on this type of watershed. The magnitude of the storms received may make the model somewhat conservative, but even so it is not restrictive on the design of the roads, and its simplicity makes it a readily applicable tool for protecting water resources while minimizing costs of road construction.

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